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A RATIONAL THEORY OF THE CUP ANEMOMETER

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NOMENCLATURE AND SYNOPSIS

W = true wind travel in unit time. (To be specific in this text and to accord with universal American usage, I shall generally use inches for cup wheel dimensions, and express wind travel in miles per hour.)

W_o = a small wind movement just adequate to keep a cup wheel turning against friction. The approximate value of this constant can be assigned by judgment or otherwise if specific observations are wanting.

n = observed number of cup wheel turns during time, t seconds. This is the only fundamental performance-index of a cup wheel that can be directly measured during a test; velocity $= n \div t$.

N = number of cup turns per unit wind travel at assumed uniform velocity W miles per hour $= 3600n\ (sec.) \div tW$. Observations show that the value of N drops to zero at certain low wind velocities, increases rapidly and approaches a limiting high value for each particular instrument as the wind attains hurricane speeds.

V = wind travel *indicated* by any cup wheel, that is the number of mile marks recorded in one hour, or the indicated velocity by some scale.

v = linear travel in unit time of cup wheel centers corresponding to actual wind travel, W.

F = *actual* anemometer "factor" $= W \div v$. This is *not* a constant as often assumed and asserted. It is large at low velocities, falls off rapidly as wind speed increases, and at high velocities approaches a limiting low value which corresponds reciprocally to the limiting high value of N.

L_{cdff_o} = a single conventional symbol which denotes the five essential form and dimensional characteristics of cup wheels, namely, L, the length of arms from axis to center of open face of cup; c, the number of cups; d, diameter of cup involving also diameter of arms if not quite negligible; f, the form of cups, whether hemispherical, cylindrical, conical, parabolic or otherwise; f_o the friction characteristics, especially at low velocities.

A = the anemometer "index." This is an entirely arbitrary but indispensable number which must be incorporated in the gear train or other indicating scale of every instrument. It represents the constant number of cup wheel turns per mile mark, that is, of each registered or otherwise indicated mile of wind travel.

By definition and rigorous analytical relations, for English units

$$NF = \frac{10084}{L_{cdff_o}}$$

By this equation it is the product NF which is rigorously constant for any one cup wheel, not F alone, as often asserted.

By definition the number of cup wheel turns per hour in a uniform wind, W is given by the following equation of identity:

$$NW = AV \qquad \text{(I)}$$

For finite and positive values of N and W this is a rigorous and perhaps the most important fundamental equation in all anemometry. Its practical utilization, however, requires an analytical relation between N and W. The derivation of this is a problem in theoretical aerodynamics which has not yet been solved adequately. Nevertheless, from the empirical analysis of all the observations available it is found that the performance of all cup wheels tested can be accurately represented by equations of rectangular hyperbolas whose asymptotes are parallel to the coordinate axis. The equation is

$$N = \frac{b(W - W_o)}{W + a} = \frac{10084}{LF} \qquad \text{(II)}$$

The constants b and a must be evaluated from an adequate body of observational data over as great a range of values of W as possible.

Replacing N in (I) by its value in (II) we got a final unique equation for all cup anemometers.

$$V = \frac{\frac{b}{A}(W - W_o)}{1 + \frac{a}{W}} \qquad \text{(III)}$$

The constants W_o and a are small and very nearly the same for all cup wheels. The equation is universal for all instruments because we are free to give A such a value that the ratio $b \div A$ is the same for any design cup wheel we may wish to employ. This forcefully demonstrates that *whether the indicated velocity, V, agrees closely with W depends quite wholly upon the value chosen for A in equation (III) and not as some suppose and assert upon the dimensional characteristics of the cup wheels themselves, which characteristics are effective almost exclusively in changing the value of b.*

Observational data are as yet too meager to formulate the values of b and a in their full relations to wheel dimensions. From all the data we have we find the value of b for any cup wheel with arms ranging from 2.5 inches to 9 inches, and with 3 or 4 cups from 4 to 6 inches in diameter, can be quite accurately computed by the equation

$$b = \frac{5247.8 - 17.78\ L}{L + 0.7976} \qquad \text{(IV)}$$

INTRODUCTION

In 1888 the writer brought to completion an investigation to find corrections to deduce the true from the indicated wind velocities which were being obtained by the use of the standard Weather Bureau anemometer, composed of four hemispherical cups 4 inches in diameter on arms about 6.72 inches long and assumed to make 500 turns per mile of wind travel, regardless of the wind velocity.

The investigation consisted, first, of tests conducted in the great closed court of the Pension Building by means of a large hand-driven whirling machine. Owing to the limited power available the maximum test velocities just reached 35 miles per hour. Second, the tests were extended to a maximum *indicated* wind velocity of about 50 miles per hour (true velocity about 40 miles per hour) by open air comparisons on Mount Washington, N. H., in which flat pressure plates exposed normally to the wind were used to check the extension of results to the higher velocities.

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Notwithstanding the limited and very simple apparatus employed in these quite amateurish investigations, the results attained have stood the test of time in a highly remarkable manner.

In order to permit of calculating corrections at velocities far beyond those observed in the tests, a special form of purely empirical equation was adopted, which in the judgment of the writer seemed to safely extend the performance of the anemometers up to 90 or 100 miles per hour *indicated* velocity. The formula is:

$$\text{Log } W = 0.509 + 0.9012 \log v$$

W = true velocity, v = linear velocity of cup centers. The gear train of these instruments is such that the linear cup velocity is one-third the indicated velocity.

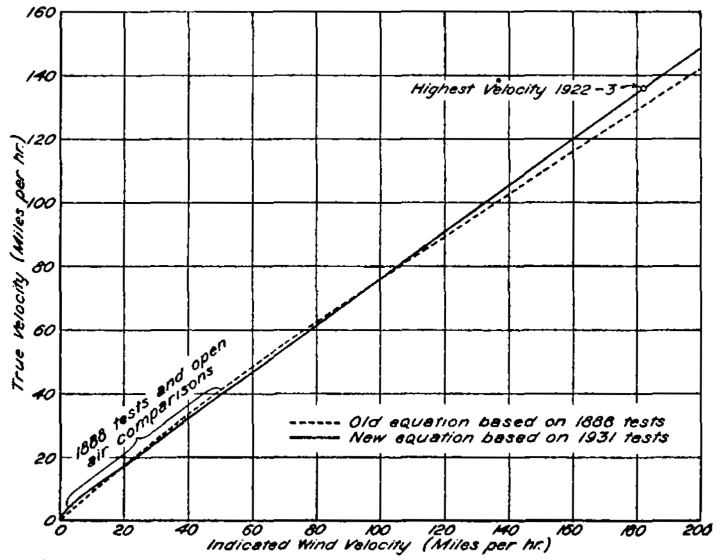

FIGURE 1.—Representing comparison between indicated and true wind velocities for the old standard 4-cup anemometer, geared 500 turns per mile, as computed by the logarithmic equation deduced from experiments in 1888, based upon tests below 50 miles per hour, and the new equation based on tests at the Bureau of Standards in 1922-29, at a maximum velocity of nearly 140 miles per hour

The dotted line in Figure 1 shows this equation over the range of true wind (scale at left) from 0 to 140 miles per hour. The full line in the same diagram shows the true relation between indicated and actual velocities for identically the same anemometer forms. This line is based on the tests made during 1922, in the wind tunnels at the Bureau of Standards, by Messrs. Fergusson and Covert of the Weather Bureau staff.

Since 1890 the bureau has disseminated tables of anemometer corrections based on the logarithmic curve extended up to 90 miles per hour, but it continued to enter *indicated* velocities in its records, believing that the correction tables should await further verification at high velocities before the actual application of corrections to the records was justified. The diagram clearly demonstrates that the velocity given by the logarithmic equation does not differ from what we now believe to be the true velocity by as much as 1 mile per hour, until a high velocity of at least 110 miles per hour indicated velocity is attained.

The equation for the full line is the new rational theoretical equation which it is the purpose of this paper to explain and discuss.

The line is a portion of an hyperbola having the following general equation:

$$V = \frac{b'W^2 - f'W}{W + a'}$$

The terms in this equation are, V = indicated velocity, W the true velocity of the wind, b' is the principal constant and is a function of the number, form, and diameter of cups, length of arms, friction of the instrument, etc. The term f' is a special friction factor depending upon the *friction at very low velocities*. Finally, a' is a small constant which defines the position of one of the asymptotes of the hyperbola; thus when $W = -a'$, $V = \infty$, that is, the axis of V is parallel to one asymptote.

This form of equation is found to fit all the tests made by Fergusson and Covert, which include a total of more than 100 individual tests [1] on various cup wheels of the old standard type, all assumed to be practically identical. Some cup wheels were of copper, some, rather lighter, of aluminum; some with, others without, bracings; the spindles in some cases turned in ball bearings, in plain bearings in other cases.

Many additional tests were made on a wide variety of 3-cup wheels ranging from small kite anemometers to the largest, consisting of 6-inch cups on 8.56 inch arms. It is clear that the hyperbolic equation suffices to represent all these tests in a very satisfactory manner.

With this introductory description we pass at once to a theoretical survey of the problem.

Technical considerations.—Whenever any anemometer cup wheel or other form of rotation anemometer is placed for test in a wind stream which flows at either a steady or variable known speed, there is just one important aerodynamic effect which can be most easily and most accurately measured of all. That is the number of revolutions of the rotor per minute or second. This feature of cup wheel performance is a fixed invariable characteristic of each particular cup wheel or other rotor at each particular velocity, and is wholly independent of any arbitrary artificial assumptions or any kind of control on the part of the operator.

Passing over all of the methods commonly well known to all students of anemometry for measuring cup wheel performance, the best and most direct methods give us two simple numbers, n = number of rotor turns executed in time, t seconds, from which

$$n \div t = \text{cup wheel turns per second}$$

With these data are of course associated the true velocity, W, of the wind stream causing the cups to rotate. Accordingly, for American anemometers intended to measure wind in miles per hour we may write

$$\frac{3600.n}{tW} = N \qquad (1)$$

That is, N = number of cup wheel turns per unit wind travel. This is the most basic and fundamental performance-index of any cup wheel that can be formulated. It is a specific datum for each wheel. All tests of any consequence show that it is definitely a variable, not a constant, and a function of W, and the fixed dimensional characteristics of the cup wheel, including the friction of the revolving mechanisms which carry the wheel.

Any one who watches the behavior of, say two or more, of the standard Weather Bureau anemometers when freely exposed near each other in very light winds, can not fail but he impressed by the fact that at times some of the cup wheels will stand motionless, others will just barely turn, while some may possibly turn visibly faster.

[1] Throughout this paper the word "test" is used to designate any operation out of which we secure two comparable items of data; (1) the true velocity of a stream of wind (assumed to be reasonably uniform), (2) the angular velocity of the rotor of the anemometer exposed in the wind stream.

These features of characteristic behavior can easily be tested and observed on almost any quiet early morning. Differences in air currents affecting the several instruments, although a factor, do not explain the effects. The instruments may differ, or they may all be nominally identical but differ slightly in friction. Without further analysis we all know, of course, that all cup wheels cease turning at some very low wind movement. Is it not absurd to affirm that just because the recent standard 3-cup wheels are alleged to make 640 turns per mile of considerable wind movement, they also continue to make 640 turns per mile when the wind is so light that it is just able to keep the cups turning? Instead, the cups make only a small number, perhaps only 100 or 200 turns per mile. The number per mile increases rapidly as the velocity increases, and finally, as conclusively shown by the observations, the value of N for a given cup wheel asymptotically approaches an upper limit.

True anemometer factor.—All authorities and writers, if asked to define the term "factor" as used in anemometry, will doubtless answer, it is the ratio $F=W\div v$, the ratio of the true wind velocity divided by the linear velocity of the cup centers. We can not *assume* a value for either F or v. We can not measure either of them directly. All we can do in making a test is to select a value of W and take the values of F and v just as they come by computation from the test. The only basic equation for this purpose is the following, in which $L=$ length of arms in inches.

$$v=\frac{2\pi L\ N\ W}{5280\times 12}$$

Transposing the terms

$$N\frac{W}{v}=N\ F=\frac{10084}{L_{cdff_o}} \tag{2}$$

Cup-wheel characteristics.—The composite symbol L_{cdff_o} is offered to designate the five essential characteristics of any cup wheel, as follows: $L=$mean distance from the axis to the center of the open face of the cups; $c=$ number of cups, doubtless limited to 3 or 4; $d=$diameter or like dimension of cups, including arm features if essential; f designates the form of cups, whether hemispherical, cylindrical, parabolic, conical or other form; finally, f_o represents the friction characteristic of the cup-wheel axis, especially at low velocities.

For any one cup wheel (waiving deformations and slight variations of friction), each one of the five features is of course fixed and invariable in one and the same instrument, but variations in any one of the features in different wheels must be reflected in the value of N for a given value of W. However, all the observations available clearly indicate that variations in L are most influential in causing values of N to differ widely for different cup wheels. Since for one and the same wheel the second member of equation (2) is rigorously a constant, and since all observations show N varies from low to high velocities, obviously it is the product $N\ F$ which is always rigorously a known constant and never F alone. This known constant depends primarily upon L, but nevertheless is subject to certain small secondary effects due to the characteristics $cdff_o$. The observational data as yet available are not sufficiently extensive and refined to permit the effects of these features to be definitely evaluated. It is clear, however, that they are small, and having adequately discussed the significance of the subscripts they may be suppressed hereafter, provided the effects themselves are remembered and considered in subsequent developments.

If we regard L in equation (2) as a constant subject to changes by steps at will, the equation represents a family of rectangular hyperbolas whose asymptotes are the coordinate axes.

Figure 2 shows these curves for cup wheels with arms from 1 inch, which is quite too small for any practical measuring instrument, up to the great Kew anemometer with arms 24 inches long. This latter may possibly be quite too large for practical cup wheels, but to the student who appreciates the full significance of Figure 2, it is plain that cup wheels with arms at least 7 inches long or even longer, have a number of superior advantages; lower angular velocity, nearly the same value of the factor for similar values of N and for arms of quite different lengths.

All I have said under this caption of *true factor* relates rigorously to equation (2). Repeating somewhat for emphasis, we are free to select any cup wheel we please

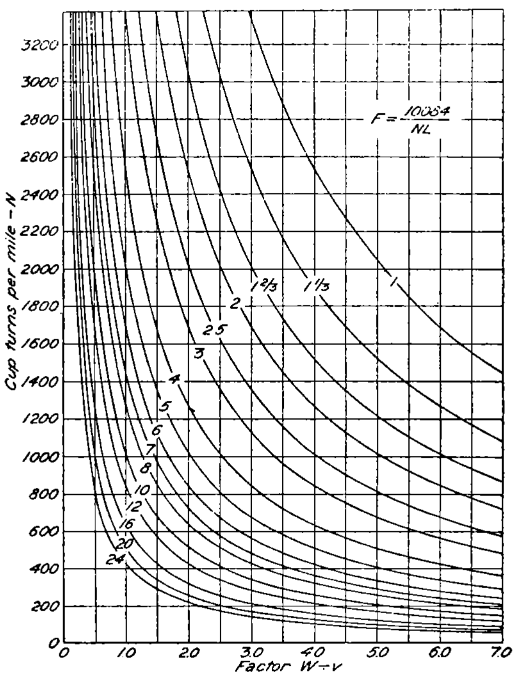

FIGURE 2.—Family of curves showing values of anemometer factor, F, in relation to the turns per mile, N, and the length of cup wheel arms, L, in inches, indicated by numbers on the line

and we may choose approximately the wind velocity for a test. Once exercised these choices end it. We have no *a priori* control whatever over the values of either N, F, or v. They must be taken just as they come from the test and computations. Emphasis is laid on these matters in order to call attention to what I regard as untenable reasoning on the part of anyone who saddles upon the equation $n\div t=$revolutions per second, the artificial assumption that a single turn of a cup wheel represents, say one meter or one one-thousandth of a mile, or any other unit of wind travel. At the very best, the assumption can be true for only some one wind velocity, and that an unknown one. Moreover, to make such an assumption at the outset is to presume already to know that which it is the main purpose of the investigation to ascertain.

It has been clearly shown that upon the basis of its definitions alone, including rigorous equations of relation, there can not be any such thing in practical anemometry as cup wheels with "constant factors," except by ignoring friction effects at low velocities and disregarding small but important and significant changes at high velocities. All such assumptions and approximations only becloud clear thinking and obscure the more important facts sought in any serious investigation. Moreover, they tend to suppress and minimize the real errors of those cup wheels which are said to have constant factors, and even lead to the false conclusion that some particular cup wheel gives true wind velocities over a wide range without the need of tables of correction, whereas its real errors are large.

False "factors."—If we answer such questions as, What is the factor for the new 3-cup anemometer? The old 4-cup standard? etc., by saying that the factor is 2.50 for the 3-cup instrument and originally 3.00 for the old standard, we are using the word factor loosely with an entirely different definition from that prescribed by equation (2). The gear train[2] and dial subdivisions including electrical registration devices in these instruments *indicate* 1 mile of wind travel for each 640 cup wheel turns in the 3-cup wheel and 500 turns of the old standard. Our unwitting loose usage requires that the false factor be defined by the equation

$$F'=2.50=\frac{10084}{6.302\times 640}\text{ and }F''=3.00=\frac{10084}{6.\ 72\times 500}.$$

This concept of the idea factor is rigorous and specific enough in itself, but the wind velocity, W, is wholly omitted and as a general definition it can not be reconciled with the age-old definition and ratio, $F=W\div v$. This usage is too vague and indefinite to deserve a place in scientific anemometry. Moreover, it is believed to have been convincingly shown by rigorous equations that the true factor changes value progressively with wind velocity. At very low velocities the value is very large. It falls off rapidly as the velocity increases, and steadily approaches a limiting low value which corresponds reciprocally to the limiting high value to which N approaches at very high velocities. It is urged that the inconsistent and unwarranted usage of the ratio $W\div v$ as a constant for any cup wheel be discontinued in scientific writings on anemometry.

Anemometer index.—Before any rotation anemometer can be used in any practical way for measuring wind velocity, whether by the ordinary mile-marking registers, by electromagnetic indications, or by the Richard method, it is first necessary to choose a definite index number, A, which is rigorously a constant and which must be incorporated in the gearing and other registration arrangements of the instrument. This number is 500 in the old standard 4-cup anemometer and 640 for the new 3-cup wheels. They are respectively the number of cup-wheel turns alleged to *indicate* a mile of wind travel. By definition and fact this number, when incorporated in the gear train, becomes absolutely a constant for all wind velocities for each anemometer to which it is given, and no instrument can be used without a number. Up to the present time this indispensable number has never been given a specific name. How fortunate it would have been had Robinson called this number the anemometer "factor," or perhaps its index, instead of supposing the ratio $W\div v$ was a constant and calling that variable the factor.

Brushing away the fallacious thesis of *assuming* a factor and computing a value of A to correspond, it is easy to show that the choice of a value for A is purely an arbitrary matter, although a wise choice must of course be made. It is wrong, for example, to say that the 3-cup anemometer indicates more nearly true wind velocities over the entire range than the old 4-cup standard itself. It is altogether a choice of the index number.

A method for the wise choice of the index number will be given presently. In the meantime it is urged that proper recognition be accorded to this important arbitrary number designated A and defined thus:

A = anemometer index = the arbitrary number of cup-wheel turns chosen to correspond to the registration of so-called mile marks or other scale values of *indicated* wind travel.

Final general equation.—Let V = the number of mile marks recorded or otherwise *indicated* in one hour at any time when the wind travel is W miles per hour and the cups make N turns per unit wind travel. Purely from these definitions we may write at once, as an equation of identity

$$NW=AV \tag{3}$$

For positive values of N, W, and V, both sides of this equation express simply the total number of cup-wheel turns per hour, and the equation is the basic fundamental equation for all anemometry. Every investigation ever made over any range of velocity shows N is a variable; therefore it is physically impossible for V to be the same as W for any cup wheel, except at some velocity depending upon the choice of A.

By replacing N in equation (3) by its value drawn from equation (2), we get a new rigorous equation between V and W involving F and the form and dimensional characteristics of a cup wheel, thus:

$$\frac{W}{F}=\frac{AV}{10084}L_{cdff}. \tag{4}$$

This equation is cited chiefly to show its availability to those who may prefer to follow up the analytical relationship between W and F rather than those between N and W. Both equations (3) and (4) rigorously satisfy all definitions equally, and values of N and F must be classed alike as direct observations which necessarily flow as specific results from each test measurement. (*See* values in Tables I, II, and III.)

Although independent computations of equation (4) have been made for both the copper and aluminum 4-cup wheel tests, it is so much simpler and more rational to use the NW relationship that that has been adopted as the regular program.

Throughout all the foregoing discussion of technical considerations, empiricisms of every sort have been studiously excluded, especially from the equations, and I have finally attained the rigid equations (3) and (4) giving the relation between an indicated wind velocity V and the true velocity W. The practical utilization of these equations requires that proper analytical relations be formulated between N or F and W. Theoretically this is a problem in the aerodynamics of cup-wheel performance, but unfortunately no satisfactory solution of it has as yet been offered, and we are compelled to seek some empirical solution which satisfies the rather considerable body of data now for the first time available. This leads us naturally to the next section.

TEST OBSERVATIONS AND THEIR ANALYSIS

Guided by the foregoing considerations, all the original observations made by Messrs. Fergusson and Covert on 3 and 4 cup anemometers normally exposed in the wind

[2] See caption Anemometer Index.

tunnels at the Bureau of Standards have been reduced to simultaneous values of W, N, and F.

Tables 1, 2, and 3 contain the entire body of original data with explanatory and descriptive material. Column 2 gives the carefully observed velocity of the wind stream in meters per second.[3]

The third column contains the so-called indicated velocity on the basis explained in the caption to the tables. Column 4 contains the direct index, N, number of cup turns per mile of wind, freed from all arbitrary assumptions of any kind. The fifth column contains the actual so-called "factor" for the particular cup wheel under test and for each velocity. Finally, the column of specifications supplies the essential dimensions, etc., concerning the cup wheels and spindles.

Measured track-walking tests.—Very few of the wind tunnel tests were made at velocities as low as 10 miles per hour. They thus fail to show what happens at low velocities. To supply this information in a small way the writer instituted quite a number of tests in which various anemometers were carried on a staff by a person walking along a measured line or track laid off upon the balcony of the closed inner court of the Weather Bureau. The track was 0.0210 miles in length. A second person carried a small chronograph upon which the number of circuits around the court, the turns of the cup wheels under test, and the time were all accurately recorded. Velocities from under 1 to over 3 miles per hour were easily maintained in these tests.

The results confirmed the reasoning on low-velocity performance previously given and fitted in very well with the wind tunnel tests. Nevertheless, troublesome natural air currents, especially through open portals leading onto the balcony, caused some anomalous values of N and demonstrated the need of numerous tests and much care if exact values at the lowest velocities are to be secured. On the other hand, walking tests of this character under favorable conditions have great advantages over the use of ordinary small-sized whirling machines.

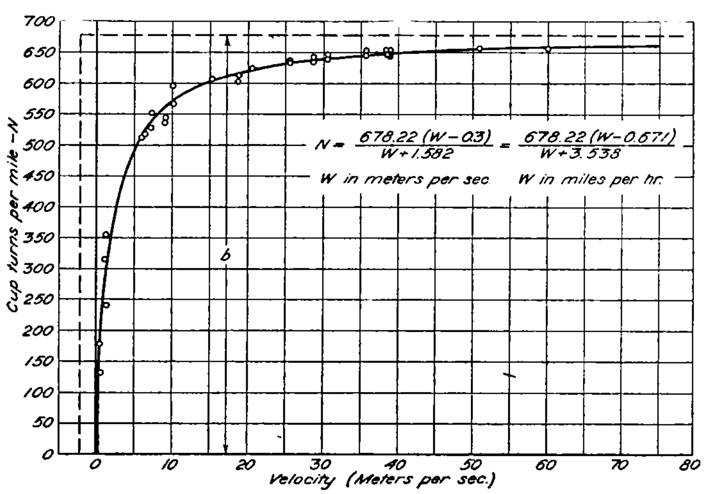

FIGURE 3.—Tests on old standard copper cup wheels with rectangular hyperbola, computed by equation as given on diagram

While the analytical theory already given under the caption Technical Considerations was in the process of gradual development, a survey was also being made by means of plots of various groups of observations taken from Table 1, including the fitting of parabolas, arcs of ellipses, etc., to the data. Mr. Grimminger, who was assisting in the study at this time, casually pointed out that an equation of the form, $N=\frac{bW-f}{W+c}$ might be useful. Trials soon proved this to be a happy suggestion. Obviously the curve is a hyperbola with its asymptotes parallel to the coordinate axes.

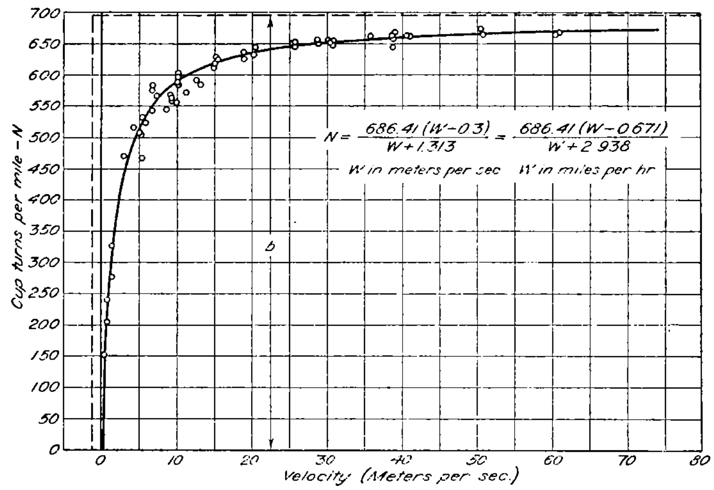

FIGURE 4.—Tests on aluminum cup wheels with rectangular hyperbola, as given by equation on the diagram

Old-standard copper and aluminum cup wheels.—The large number of observations made on several sets of the old-standard cup wheels furnishes the best test we have of the hyperbolic equation, also a much more dependable value of the performance of these cup wheels than of that of any of the 3-cup wheels tested. All the 4-cup test values are shown by dots in Figures 3 and 4. A line is also shown in the diagrams threading its way in a highly satisfactory manner between the whole series of observations, including those at the very low velocities.

A single run on the so-called heavy-pattern seacoast anemometer, with cup arms braced by thin metal bands flatwise to the wind, is given in run 33. While there are minor structural differences between this anemometer and the others, the test data for it are so discordant that they were omitted in computing the constants of the representative line. The seacoast cup wheel ran decidedly too fast at low velocities, although its known excess of friction should make it run too slow, whereas at high wind velocities, when friction is of less consequence, the wheel ran altogether too slow. The causes for these results are quite unexplained, unless due to excessive friction under lateral pressure in the top bearing or the wind resistance of the flat bands.

In Figure 4 are shown the 68 test observations upon four different sets of aluminum 4-cup wheels. The representative line threading its way through the somewhat more scattered observations in this case is also shown.

Figure 5 with the computed line and its equation represent tests from a single run on 3-cup wheel No. 30, which is the only 3-cup wheel originally tested having dimensions closely comparable with the so-called 3-cup standard anemometer subsequently adopted. Finally, Figure 6 represents three series of tests of standard 3-cup anemometers carried on Friez magnetor indicating mechanisms, as explained in the heading of the table.

A considerable variety of 3-cup wheels with other dimensions also were tested, generally only in a single run, as shown in Table 2. Equations have been computed for

[3] Except in the case of the tests on the magneto anemometers, the original observations of wind velocity were made in meters per second. To avoid local inaccuracies entailed by rejection of decimals incident to conversions to miles per hour, the unit meters per second was retained throughout all the numerous least square computations. The conversion of the final equations to English units involved, of course, a very simple transformation of the constant with no loss in accuracy.

all of these runs, and it is found that with few exceptions they are all well represented by a rectangular hyperbola whose asymptotes are parallel to the coordinate axes. These asymptotes are shown on the drawings by heavy broken lines. The general equation for the lines threading through the observations in a form most convenient for computing its constants by least square methods is

$$f+bW+aN+NW=O \tag{5}$$

In a word, this is seemingly the analytical relationship we seek between N and W. We have not at present

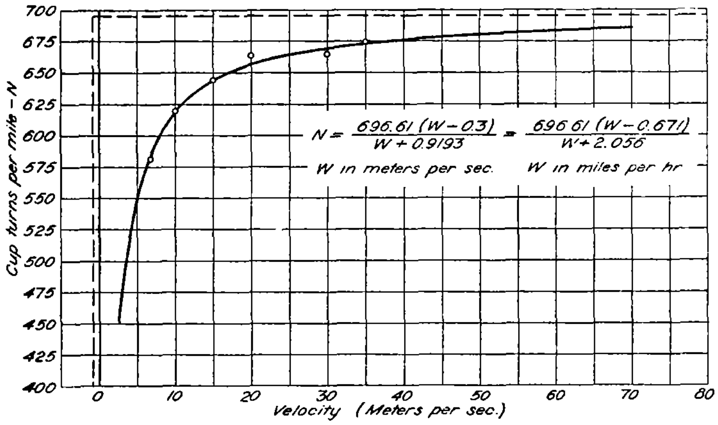

FIGURE 5.—Single run of tests on cup wheel No. 30, like the 3-cup standard wheel finally adopted, with equation of hyperbola

any rigorous aerodynamic *proof* that this form of equation *should* represent the NW relationship, but its strongest claim for acceptance is that it seems to fit all observations available from the very lowest to the highest velocities, *especially for those types of cup wheels which are best suited to meet meteorological requirements*. The numerical constants for the several cup wheels are given in the equations on the diagrams and in Table 4, to follow.

To discuss these equations briefly, it will be noticed that the coefficient b in equation (5) always takes on the negative sign, and from the diagrams we see that as an ordinate, b fixes the position of the asymptote parallel to the axis of W. Also that b is the limiting large value which N asymptotically approaches as the wind velocity becomes very high. It is also plain from the diagrams that the abscissa, $W=-a$ locates the other asymptote parallel to the axis of N.

Finally, when $N=O$, $W=-\frac{f}{b}$. This introduces a very important relation involving the effects of instrumental friction which deserves rather full analysis.

Friction.—Little experimental data of any kind are available by which the quantitative effects of friction in anemometry can be evaluated. Friction generally is regarded as negligible, and in fact is relatively unimportant in instruments of good design if they are occasionally oiled and otherwise properly cared for. Nevertheless, its effects can not be ignored, especially in the case of winds of low and moderate velocity or in any serious theoretical analysis. Two aspects of the question require consideration.

(*a*) There is the irreducible minimum of the friction which operates when the cups are turning in very light winds and which may stop rotation altogether while the wind continues to move at some very low velocity, W_o, which I assume is just high enough to keep the cups turning. In this concept of W_o we must discriminate between friction of rest, which is often greater than the irreducible minimum friction of slight motion.

(*b*) The second effect of friction, about which still less is actually known than the (*a*) effect, is due chiefly to the sliding action of the spindle in the top bearing. Increase of wind causes this to increase nearly as the square of the velocity and operates to lessen the number of cup wheel turns per unit of wind travel which would be attained at high velocities if all friction were zero.

All friction effects are controlled and minimized by the use of high-grade construction, and especially the adoption of correctly designed ball bearings.

Although certain of the wind tunnel tests were made with ball bearings and others with plain sliding bearings, the small quantitative differences can not be segregated from large accidental fluctuations of unassignable causes. This of itself may indicate that friction in first-class instruments on the whole is small and unimportant, except at low velocities, which I shall now consider somewhat further.

Transposing the terms in the equation $W_o=-f\div b$ we get,

$$f=W_ob \tag{6}$$

The quantity W_o must always have a small and positive finite value; and since b is always negative, f is therefore positive. In effect, this constant measures the frictional resistance of the cup wheel mechanisms at low velocities; *that is, W_o is the low velocity which is just sufficient to keep the cup wheels turning against the friction of the bearings.* If we have a strong body of observational data at low velocities to statistically balance the numerous results of high velocity tests, then reliable values of f, a, and b will flow from a least square analysis

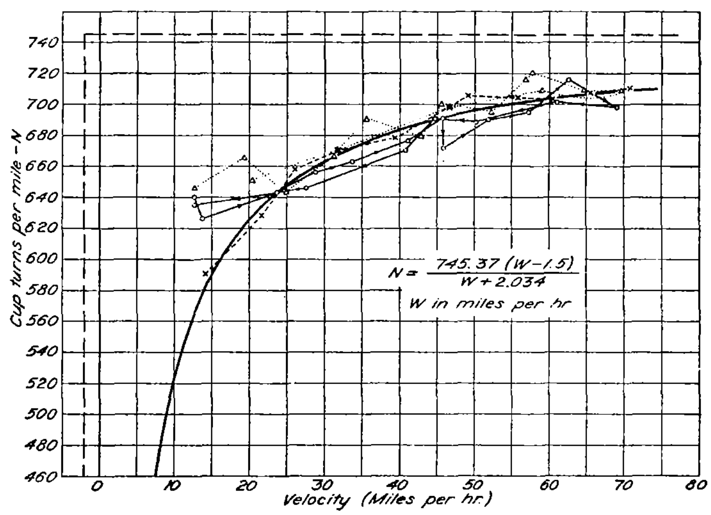

FIGURE 6.—Three separate runs of magneto anemometers actuated by standard 3-cup wheels, with and without vane, with the hyperbolic equation. Circles, tests forward and back on magneto without vane. Triangles, tests forward only on magneto with vane removed. See Table 3

of all the observations, and a trustworthy value of W_o will result from equation (6). Unfortunately, however, nearly all the wind-tunnel tests are at velocities above 13 to 15 miles per hour, which are quite too high to tell us anything about what the cup wheels do between 0 and 15 miles, which range in velocities represents perhaps more than 75 per cent of the velocities at ordinary meteorological stations. Under these circumstances the vagaries and inaccuracies in the high-velocity data will cause calculation of constants not controlled in any way to give values of W_o which may sometimes be too large, or it may take on negative values which also is irrational. Although we have the few observations obtained by the track-walking tests, these are inadequate for all the cup wheels. Therefore, to assure that our final equations shall give rational values for W_o I shall use equation (6) as an equation of condition in the least square computations. We know from the track-walking tests and other information that the value of W_o must lie between one-half and 1½ miles per hour for most instruments, depending on what may be known about their friction. This enables us to replace f in the general equation (5) by its value $f=-W_ob$.

By this treatment the low velocity friction term is retained in the final general equation in the form W_ob, which can be evaluated at any time to satisfy any new knowledge that may be acquired as to the condition of an instrument and the best value of W_o. In subsequent equations bW_o will therefore take the place of f, and $W_o=-0.3$ has been used for computations when W is in meters per second except in the case of the magnetos and certain heavy cup wheels for which $W_o=-0.5$ is used.

The equation for actual calculation of the constants a and b thus becomes:

$$(W-W_o)b+aN+NW=O \tag{7}$$

Table 4 gives the values of the three constants for practically all the cup wheels tested whose dimensional characteristics are fairly comparable and suited to meteorological needs. With few exceptions the values of a in all the equations are small and nearly the same. Since a is the constant which gives curvature to the anemometer law, there is no justification for the statement sometimes made that the *indicated* velocities by one cup wheel are more nearly true wind velocities than are those by another. When the gear train—that is, the arbitrary constant A—is chosen with equal fairness to all, the run of hourly *indicated* velocity by all will be essentially identical, as will more definitely appear later.

Systematic difference between aluminum and copper cup wheels.—The equations on Figures 3 and 4 for the copper and aluminum cup wheels show a systematic difference, especially in the value of b, which affects the values of true velocities, especially high velocities. These cup wheels are used in bureau equipment indiscriminately, and we have no explanation for the systematic difference actually shown in the data. The aluminum and copper cup wheels tested have measurably identical dimensions throughout, although some copper cup wheels are strenthened by bracings of thin flat bands edgewise to the wind. Such cup wheels are slightly heavier and by tests, as well as by their equation, they run appreciably slower at moderate and high velocities than the aluminum cup wheels. Nevertheless, the track-walking tests show very small effects from friction at low velocities. We think the explanation of the difference must also be sought in some of the aerodynamic effects.

Solving equation (7) for N (remembering that b is negative) gives

$$N=\frac{b(W-W_o)}{W+a} \tag{8}$$

Replacing N by its value in terms of F from equation (2) gives the companion analytical relation between F and W as follows:

$$F=\frac{\frac{10084}{bL}(W+a)}{W-W_o} \tag{9}$$

Substituting for the value of N in the basic equation (3) its value from equation (8), and writing the resulting equation in a form to show its universality, we get

$$V=\frac{\frac{b}{A}(W-W_o)}{1+\frac{a}{W}} \tag{10}$$

The companion equation, using F instead of N by substitution of (9) in (3) also gives after a few transformations,

$$V=\frac{\frac{F'}{b'}(W-W_o)}{1+\frac{a}{W}} \tag{11}$$

The mathematician will, of course, readily see that equations (10) and (11) are literally equations of identity.

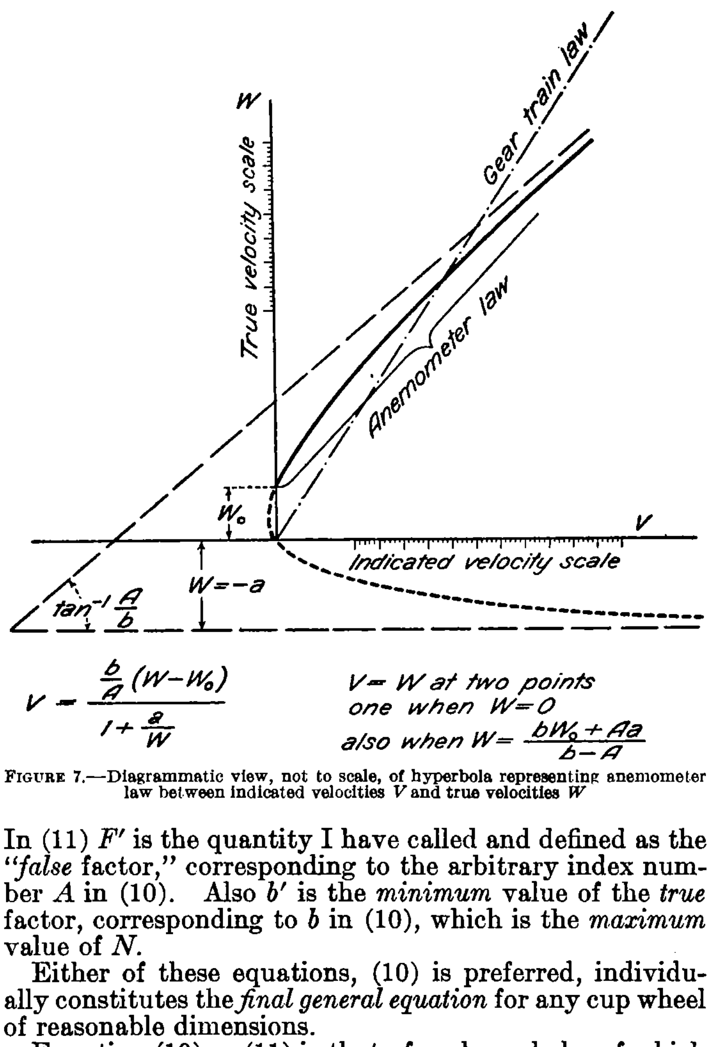

FIGURE 7.—Diagrammatic view, not to scale, of hyperbola representing anemometer law between indicated velocities V and true velocities W

In (11) F' is the quantity I have called and defined as the "*false* factor," corresponding to the arbitrary index number A in (10). Also b' is the *minimum* value of the *true* factor, corresponding to b in (10), which is the *maximum* value of N.

Either of these equations, (10) is preferred, individually constitutes the *final general equation* for any cup wheel of reasonable dimensions.

Equation (10) or (11) is that of an hyperbola, of which one branch is such as shown in Figure 7. The dotted portions of the curve are, of course, not relevant to anemometry, but the full-line portion is believed to give the most exact analytical representation of cup-wheel performance yet offered. It covers the complete range of velocities from $W=W_o$ to the highest velocities yet attained in any tests available for these studies.

One of the asymptotes of the curve is parallel to the axis of V, and it cuts the axis of W at the point $W=-a$.

The other asymptote makes an angle with the axis of V whose tangent is $+\frac{A}{b}$. The axis of the hyperbola and its intercepts with the coordinate axes can easily be evaluated by the methods of analytical geometry. It is obvious also that a is a small, nearly constant parameter of the equations which measure the *curvature* of the anemometer law.

The reader must remember that equations (10) and (11) represent not only the 101 test values on the copper and aluminum cup wheels, but in addition about 83 test values on 13 different sets of 3-cup wheels of widely varying dimensions. This representation embraces the entire range of velocities always from $W=0$ to nearly 140 miles per hour in a small number of tests, and in all other cases to a limit of nearly 80 miles per hour. The agreement between observed and computed values is particularly satisfactory for those types of cup wheels best suited as standard instruments. In a word, these equations, including the values of the constants in Table 4, are the analytical embodiment of the entire 184 test observations available.

This substantial body of evidence, based, we believe, upon a sound theory, seems to compel simple recognition and the adjustment of meteorological thought and practice in anemometry to conform to the essential facts involved therein. Some of these may be briefly summarized as follows:

(1) The form of the final equations makes it easy to see just what is analytically required in order that the indicated velocity V shall be equal to W over the whole range of scale. First, the small friction term W_o, second the small curvature term a, must both be literally zero; third, we must make the arbitrary number $A=b$. These are analytical prerequisites which this investigation shows apply to *all* cup wheels of rational character. Without hesitation, I may freely assert that not a single cup anemometer in use anywhere satisfies the requirements specified, more especially the one that $A=b$. Consequently, each type of cup wheel has its particular category of errors over the whole range of velocities, depending chiefly upon the value of the ratio $b \div A$, and in a secondary way upon the amount of friction and the value of a.

(2) *If we have any number of cup wheels whatsoever—3 cups, 4 cups, large cups, small cups, long arms, short arms—*THE INDICATED VELOCITIES *by a whole flock of such cup wheels exposed in the same wind will come out* ESSENTIALLY IDENTICAL, *provided only we choose a value of A such that for each cup wheel $b \div A$ shall be the same for all.*

Moreover, equation (10) gives us a substantial analytical basis justifying the statement that it is the choice of the constant A and the gear train of any particular anemometer, and not the choice of the form and dimensions of a cup wheel which determines how nearly V and W run in close accord over a given range of velocities.

The old standard 4-cup wheel on a gear train of 500 turns per mile was a misfit. On a gear train of 640 turns per mile its performance is superior to that of the present 3-cup standard.

(3) In the present stage of the science of anemometry we must give up the idea that there is some magical cup wheel whose indicated velocities are all nearly true velocities, and we must stop deceiving ourselves and others by suppressing or minimizing the real errors in indicated velocities by any cup wheel. The magic wheel has not yet been found. *Its discovery depends upon identification of the aerodynamic features which cause the constant a in all equations to have a small positive finite value.* When we find out how to design a cup wheel for which a will always be zero, then the hyperbola represented by equation (10) becomes two intersecting straight lines. One of these coincides with the axis of V, the other intersects at the origin of coordinates, provided the low-velocity friction is absolutely zero. Finally, this line which is the portion of the hyperbola which represents the anemometer law,—this line will cross the axes at an angle of 45°, *provided the arbitrary number A is made equal to the limiting value attained by N in very high winds.* Under these conditions equation (10) (and (11) also with slight changes in terminology) reduces to the simple form $V=W$.

These entirely rational results which flow from certain limiting assumptions go a long way toward establishing the general soundness of the analytical basis upon which the final equations (10) and (11) have been formulated.

Choice of A.—While the *indicated* velocities by all cup wheels will be essentially the same if the ratios $b \div A$ are made identical, nevertheless this should not be the sole criterion for fixing upon the best value of A in any practical case. By the basic equation $NW=AV$ it is plain that $V=W$ for those values of W near to that value which makes

$$N'=A \text{ or } W'=\frac{bW_o+Aa}{b-A}$$

This is a useful equation to guide us in the choice of the best value of A for any given case. If, for example, A is chosen equal to b, then $W'=\infty$; that is, the indicated and true velocities run in accord only at very high velocities and disagree seriously at moderate and low velocities. On the other hand, if A is made much smaller than b, then W' will have a small value; that is, the true and indicated velocities will agree closely at all low velocities, as in the case of the old 4-cup standard.

Obviously we must compromise so as to make $V=W$ at some ordinary velocity, say 30 to 50 miles per hour, according to the relative inportance we attach to the errors we must tolerate in uncorrected indicated velocities at moderate as compared with high velocities.

There is, moreover, a mechanical limitation upon the choice of A; that is, its value must be a multiple of 10, otherwise the gear train becomes complex; that is, incommensurate ratios, fractional gear teeth, etc., may be involved. We must be content, therefore, with choosing the best value of A we can, and then compute from equation (10) a suitable table of true and indicated velocities.

It is very difficult to show graphically the actual errors of anemometers if we limit ourselves to plotting W against V; that is, the relative smallness of the errors compel the use of graphs on a very large scale if details are to be brought out. However, better results with any desired degree of mangification, even in a small diagram, may easily be attained by means of a difference equation; that is, subtract W from both sides of equation (10) and after reduction we get

$$V-W=\frac{\left(\frac{b}{A}-1\right)W-\frac{b}{A}W_o-a}{1+\frac{a}{W}} \tag{12}$$

The numerator in this equation looks complicated because the make-up of its two constants is shown in full. In actual practice these reduce to a small coefficient for W and an absolute constant. For example, for the old aluminum 4-cup standard this equation is

$$V-W=\frac{0.3728W-3.8591}{1+\frac{2.938}{W}} \tag{13}$$

In this, and like equations to be given presently, it is obvious that $V-W=O$, that is $V=W$ when $W=\frac{3.8591}{0.3728}=$ 10.4 miles per hour. This means, as known since 1888, that between 0 and 15 miles per hour the indicated and true velocities agree closely by the old 4-cup standard, whereas above 15 miles per hour the indicated velocities run far in excess, all now shown to be due to the choice of the gear train of 500 turns per mile registration.

If we put the old standard 4-cup wheel on the 3-cup spindle geared 640 turns per mile registration, the equation becomes

$$V-W=\frac{0.0725W-3.6577}{1+\frac{2.938}{W}} \tag{14}$$

This gives a very satisfactory distribution of errors over the whole range of velocities. $V=W$ when $W=50.5$ miles. There is a maximum negative error of almost 2.3 miles per hour at $W=11$ miles per hour, between this and 60 miles per hour the errors are relatively small and increase steadily. It will be shown presently that these errors by the 4-cup standard on the 3-cup spindles are decidedly smaller than those for the 3-cup wheel itself. These results are shown graphically in Figure 7.

Relation of b to cup wheel dimensions.—The climax and consummation of this study will be attained if we can formulate a satisfactory equation giving the relation between the proper value of b in equation (8) or (10) and the dimensional characteristics of the various cup wheels. In the absence of much more detailed information than we yet have of aerodynamic anemometry, we must rely upon the test data available for setting up the desired relationship. All the material we have for this purpose is found in the values of b given in Table 4.

The strong body of test observations on the old standard 4-cup wheels gave very definite values of b and a for 4-inch cups on arms 6.68 inches long. These data, of course, establish one strong point on any curve representing the b, L relations. For additional points we must rely upon tests made upon a wide variety of 3-cup wheels. With very few exceptions only a single test was made upon each wheel at only five or six velocities which included neither the lowest nor highest speeds. When we notice the seemingly erratic and conflicting values of N which result from numerous tests on the 4-cup wheels, including entirely similar conflicts in the few cases of more than one test on 3-cup forms we recognize the relative weakness of the 3-cup data based chiefly on single runs on a scattered variety of wheel forms.

The inadequacy of all the data at present available has already been stressed for making the nice discrimination necessary in order to evaluate by any numerical quantity the small effects caused by changes in cup-wheel characteristics, $cdff_o$. The solution of this must be left to the future, because setting aside for the present all questions as to the effects of form and friction, we find that during the tests the cup diameters and the length of arms were varied more or less indiscriminately; that is, both L and d were frequently changed small amounts simultaneously. It is, therefore, impossible to assign any specific effect to a change of either number or diameter of cups in any particular case. The tests show that a change of a few tenths of an inch in arm length makes a noticeable difference. Small changes of both factors simultaneously, coupled with the practice of making but a single run over a limited velocity range, combine to reduce the present study to setting up a relationship between b and L as if the effects due to $cdff_o$ were negligible, which, of course, is hardly the case. More refined and extensive observations must become available, however, to remove this limitation on the present work.

Disregarding as more or less noncomparable the data for the small kite anemometers, and limiting our study to cup wheels with cups from 4 to 6 inches in diameter on arms 2.3 to 8.6 inches, I have selected 15 test values of b, two of which represent, respectively, the very strong body of results for the copper and aluminum old standard 4-cup wheels. All of these points are plotted in Figure 9. It is believed every reader will concede that the observations as a whole are well represented by the line running through them and whose equation is

$$b=\frac{5247.8-17.78L}{L+0.7976} \tag{15}$$

This in part at least is the attainment of our objective, namely, given a cup wheel of known length of arm L, number, form, and diameter of cups, equation (15) we believe gives us a very accurate value of the main constant, b, of its equation (10). For anemometers registering in English units the constant W_o in the absence of direct observational data may confidently be taken at from 0.5 to 1.5, according to the known friction of the instrument at very low velocities. In like manner the constant a may with equal confidence be taken at about 2 to 3.

Finally, for reasons already given the data available do not permit us to make any discrimination between 3-cup or 4-cup systems, which are strictly the same in all characteristics except number of cups. Equation (15) rests on 15 series of cup-wheel runs, a total of 184 test points. Only two of the sets represent 4-cup wheels, with 4-inch cups on arms 6.677 inches. One of the latter two points falls exactly on the line and the other near to it.

Judging from the occasional erratic results found in some of the test data, I am confidently of the opinion that equation (15), which is the analytical embodiment of the comparatively consistent testimony of 184 test observations, is a highly reliable equation from which to compute the performance of any 3 or 4 cup wheel having cups around 4 to 5 inches in diameter on arms up to 10 inches long, including velocity ranges from 0 to 150 miles per hour.

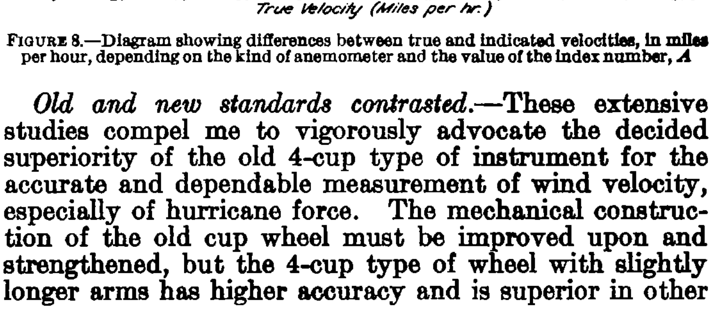

FIGURE 8.—Diagram showing differences between true and indicated velocities, in miles per hour, depending on the kind of anemometer and the value of the index number, A

Old and new standards contrasted.—These extensive studies compel me to vigorously advocate the decided superiority of the old 4-cup type of instrument for the accurate and dependable measurement of wind velocity, especially of hurricane force. The mechanical construction of the old cup wheel must be improved upon and strengthened, but the 4-cup type of wheel with slightly longer arms has higher accuracy and is superior in other ways. We do not want 3-cup anemometers for accurate measuring instruments any more than we want 3-cylinder engines for our best automobiles, and for much the same reasons—inadequate, erratic, undependable starting and driving torque.

All the equations and numerical coefficients for the 4-cup standard rests upon a strong body of observational data comprising over 100 individual test points over a wide range of velocity. In contrast to this we have only *6 actual test values* over a limited range of velocity on any 3-cup wheel whose dimensions are even approximately the same as those of the present standard. This is test wheel No. 30, point 9, and its position on the diagram

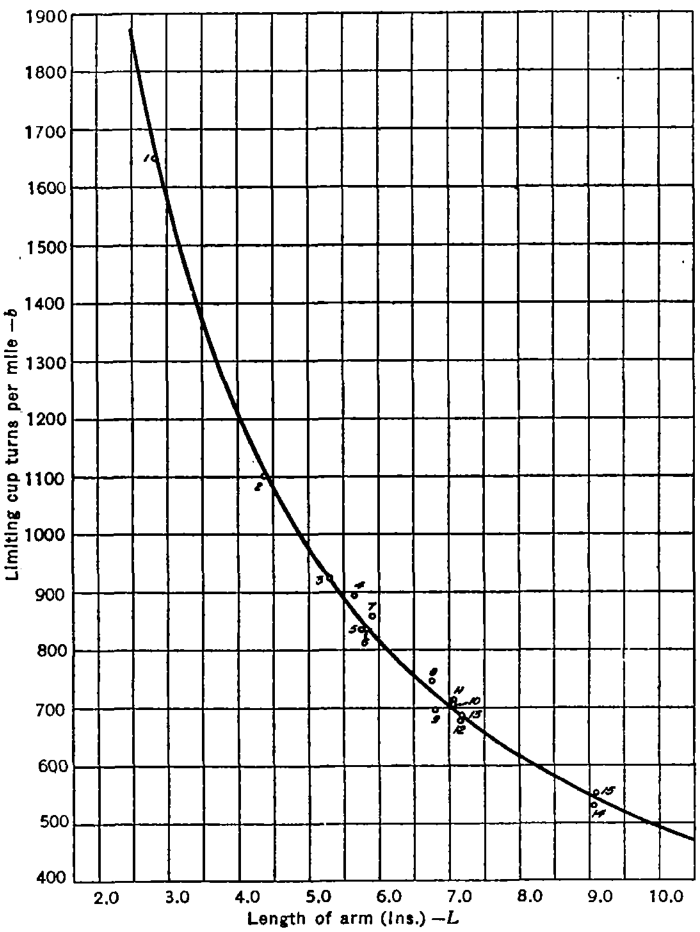

FIGURE 9.—Diagram showing the relation between the value of b in the hyperbolic equation and the length of arms of the anemometer cup wheel. Each observational point on the diagram represents the value of b in the equation for certain cup wheels represented by points Nos. 1 to 15, corresponding to the data under the same numbers given in Table 4, according to the length of cup-wheel arms

Figure 9 is inconsistent with its companion 3-cup test data. A still more serious conflict arises with the tests made long after the wind tunnel tests were completed. These comprise a series of tests on two standard 3-cup wheels on two Friez magneto instruments, also over only a limited range of velocity. These *indicate* velocity directly on a voltmeter scale and completely lack any cup turn counting or integrating gear. Such instruments are about the worst type possible to subject to any accurate test, because values of N, the only fundamental datum we can measure, must be computed from eye readings, over a longer or shorter interval of time during a test, of the fluctuating position of the voltmeter needle, the scale for which is assumed to indicate miles per hour upon the inexact thesis that the cup wheels made 640 turns per mile at all wind velocities, that the magnetos at all speeds generate 6 volts per 1,000 revolutions per minute, and that the voltmeter scale was itself correctly engraved on this basis.

Any student will recognize that these conditions constitute a serious handicap in executing basic tests on magneto anemometers. It is accordingly not surprising to find that values of b for the magnetos point No. 8 also fall well off the test data. In fact, if we take the simple mean value of the magneto and the No. 30 cup wheel tests we get a value for b which is almost exactly the same as that given for these anemometers by equation (15). That is, the general equation which agrees very well with the whole body of 3-cup test data gives us a better and more consistent value of b for the present standard 3-cup wheels than do the only sets of direct tests available themselves. Accordingly, we adopt the following equation for the new 3-cup wheel standard:

$$N=\frac{723.4\ (W-0.671)}{W+2.0452} \tag{16}$$

This gives us the difference equation of errors:

$$V-W=\frac{0.13031\ W-2.5805}{1+\dfrac{2.0452}{W}} \tag{17}$$

Contrasting this difference equation for the 3-cup standard with (14) for the 4-cup standard on the 3-cup spindle, we note that the coefficient of W in (17) is nearly twice as great as that for W in (14). This means that the errors of the 3-cup standard at high velocities are fully twice as large as for the 4-cup wheel when geared to 640 turns per mile registration. This is one among other good reasons why we advocate the superiority of the 4-cup standard.

Another fallacy exposed.—Disregarding more or less not only a rational conception of the performance of any cup wheel at very low and moderate velocities, but also the exactions of rigid definitions of F and N, including the equations of relations between them, a few writers, drawing hasty conclusions from observations mostly at relatively high velocities, are holding out the view that so-called compact cup wheels (big cups on short arms) are better for standard instruments than cup wheels of so-called slender proportions (length of arms 2 or 3 times cup diameter). In a word, the "factor" of the cup wheel of compact proportions is alleged to approach a "constant" value.

Recognizing that the body of observational data bearing upon this question is fragmentary and incomplete in important details, nevertheless I am convinced that this whole view is a misinterpretation of the evidence which when properly understood shows conclusively that for purposes of a high grade, infallible, standard anemometer for all-around station use, nearly or quite all the advantages go with *4-cup wheels of slender proportions.*

In the first place, the usage of the concept "factors" by those advocating compact cup wheels is illogical and in conflict with definitions, observations, and rigid equations. The factor is always a variable with N. It is the product $N\ F$ which is a rigorous constant, not F alone. Moreover, the ultimate result depends quite entirely upon the choice of the arbitrary number A and its ratio to the theoretical upper limit value of N which we call b, or if one pleases, to its "cousin" the reciprocal limiting value of F and the cup wheel dimensions. See equations (I) and (II).

The old 4-cup standard may be regarded as of slender proportions, and we have a large number of test observations thereon. With scarcely any exceptions these data are relatively self-consistent throughout and display a systematic relationship among themselves. In contrast to this the fragmentary and inadequate tests on the 3-cup systems, especially those of compact proportions are distinctly less self-consistent and in a few cases exhibit striking anomalies. Concerning these, and fully recognizing the paucity of observational proof, my thesis is that relatively compact cup wheels are wholly unfit for standard wind measuring instruments over a wide range of velocities.

Cup wheels of open dimensions and relatively long arms are uniform, systematic and dependable in their indications, simply because their angular velocity is relatively slow and deliberate. Both the slowly and the rapidly moving air streams *flow through* the whirling system with the minimum of vortical effects even at hurricane velocities, which must be reckoned with at times. The driving torques maintain a simple and systematic relationship with the wind travel. Quite the reverse is true in the case of cup wheels of compact dimensions. The angular velocity of these is necessarily very high, even with moderate wind speeds. The air stream *can not flow through* the rapidly whirling cup systems with sufficient freedom. Occasional observations seem to indicate that even at moderately brisk winds certain *critical aerodynamic states arise* under which a more or less stationary vortex of whirling air attaches itself to the whirling cups, whose angular velocity while this critical state exists is relatively erratic, anomalous and out of relation to angular velocities at both higher and lower wind speeds. In other words, the moving air stream does not flow uniformly *through*, but, at times at least, partially *around* these vortical whirls. Consequently, the driving torque in such cases is erratic and undependable.

Whether this thesis can ultimately be proven to be entirely sound or not must be left for future investigations. In the meantime, I must vigorously advocate the superiority of 4-cup wheels of open dimensions as the dependable standard for the Weather Bureau. The 4-cup systems are superior in point of mechanical symmetry, rigidity and strength of design, with no necessary sacrifice of lightness. Starting and driving torques are more dependable and uniform over the entire range of wind speeds commonly experienced anywhere.

CONCLUSIONS

(1) The new tests at the Bureau of Standards fully confirm the general high accuracy of the old tests on old 4-cup standard wheels, including the corrections for winds under 120 miles per hour by the old equation

$$\text{Log. } W = 0.509 + 0.9012 \frac{V}{3}$$

(2) The tests on the old 4-cup standard cup wheels constitute a strong body of observational data, and all parties to the tests are in close accord as to the interpretation of these data and the performance of 4-cup wheels.

(3) While the data in Table 4 and their interpretation exhibited in Figure 9 seem to show that there is no striking systematic difference between the performance of otherwise exactly similar cup wheels, one having 3 cups, the other 4 cups, nevertheless a stronger body of observations on a more refined basis than now available is needed to bring out the small secondary differences which it is reasonable to believe must arise in the performance of cup wheels when the characteristics other than length of arm are changed. That is, the effect of changes in the form, diameter and number of cups, and in the friction of bearings on cup wheel performance can not be definitely evaluated, except from more numerous and better tests, especially on 3-cup wheels, than now available.

In the meantime, it is believed that equation (15) gives an entirely satisfactory working value to b, depending on the length of cup wheel arm for any anemometer of the type used in ordinary meteorological observations.

OFFICIAL ACTIONS OF THE WEATHER BUREAU BASED ON THE FOREGOING

(*a*) The old 4-cup standard was restored to use at approximately all stations of the Weather Bureau, beginning January 1, 1932, following an interval of five years from January 1, 1928, to December 31, 1931, during which the 3-cup anemometer was used generally as the Weather Bureau standard, on the assumption that the indicated velocities, based on 640 cup-wheel revolutions per mile of wind, were quite approximately true velocities.

(*b*) Complete confidence seems to be justified in the considerable accuracy of the new hyperbolic equations for representing the performance of 4 and 3 cup anemometers. These equations are:

For standard aluminum 4-cup wheels, 4-inch hemispherical cups on arms 6.68 inches.

$$V = \frac{\frac{686.41}{500}(W) - .671)}{1 + \frac{1.314}{W}}$$

For the 5-inch 3-cup wheels on arms 6.29 inches,

$$V = \frac{\frac{723.4}{640}(W - .671)}{1 + \frac{2.045}{W}}$$

(*c*) In accordance with the foregoing, instructions were issued to all Weather Bureau stations to the effect that beginning with January 1, 1932, all values of wind velocity obtained from anemometers shall be corrected before being used for records, telegraphic reports, publications, or any other purpose, to the end that the best information available may be supplied to the public.

TABLE 1.—*Original observations and derived data of anemometer tests in wind tunnel at Bureau of Standards. W=true velocity of wind, V=indicated velocity by the anemometer on the assumption that each cup wheel turn represented a fixed wind travel like 0.50, 0.75, 1.00, 2.00, 2.50 or 3.00 meters, according to an arbitrary factor F and actual length of arm L. Old standard 4-cup wheels.*[1]

Date and run by serial number	Observed data. Velocities, m/sec.		Derived data		Specifications
	Wind, W	Anemometer indicated, V	Cup turns per mile N, $502.9V+W$	Factor $W+v$ $F=\frac{10084}{LN}$	
1922 Mar. 31, No. 1.	6.8	7.9	584	2.59	Nominal aluminum 4-cup wheel standard No. 1. All 4-cup wheels in Table 1 have 4-inch cups on square steel arms, set edgewise to the wind. Diameter 5/32-inch, length averaging close to 6.677 inches. Spindle with plain bearing. Low speed tunnel 4.6 feet diameter.
	10.1	12.0	598	2.53	
	15.2	19.0	629	2.40	
	20.3	25.9	642	2.36	
	25.4	32.7	647	2.34	
	30.5	39.5	651	2.32	
	35.6	46.7	656	2.30	
	38.6	50.5	658	2.30	
Mar. 31, No. 2.	6.9	7.9	576	2.62	Same conditions as in above run.
	10.2	12.0	592	2.55	
	15.3	19.1	628	2.41	
	20.4	26.0	641	2.36	
	25.5	33.0	651	2.32	
	30.6	39.4	648	2.33	
	35.7	47.0	662	2.28	
	38.8	50.9	660	2.29	
Mar. 31, No. 4.	7.4	8.4	568	2.66	Same conditions as in preceding, except ball bearings at top of spindle.
	10.2	12.2	602	2.51	
	15.4	19.2	627	2.41	
	20.5	26.2	643	2.35	
	25.6	33.2	652	2.32	
	30.7	40.0	655	2.31	
	35.6	47.1	662	2.28	
	38.9	51.1	661	2.29	
Mar. 31, No. 5.	7.2	8.0	559	2.70	Same conditions as in preceding run except plain bearings instead of ball bearings.
	10.2	12.0	592	2.55	
	15.3	19.1	628	2.41	
	20.4	25.6	631	2.40	
	25.5	32.8	647	2.34	
	30.6	39.8	654	2.31	
	35.7	47.0	662	2.28	
	38.7	51.0	663	2.28	
Apr 8, No 27.	4.3	4.4	515	2.94	Same as in preceding run with cup wheel No. 1, except high speed tunnel, 3 feet diameter.
	9.3	10.3	557	2.71	
	19.0	23.6	625	2.42	
	28.8	37.3	652	2.32	
	38.4	50.6	662	2.28	
Apr. 8, No. 31.	5.2	5.2	503	3.00	Duplicate of preceding run.
	9.3	10.4	562	2.69	
	19.3	23.6	625	2.42	
	28.8	37.2	650	2.33	
	38.4	50.5	661	2.29	
	50.7	66.7	662	2.28	
	60.8	80.8	668	2.26	
July 21, No. 49.	6.7	7.2	541	2.79	Cup wheel No. 1, same as in preceding, with plain bearings and low speed tunnel.
	10.2	11.8	582	2.60	
	15.3	19.1	628	2.41	
	25.5	32.8	649	2.33	
	38.7	49.6	644	2.35	
Apr. 8, No. 28.	5.4	5.0	466	3.24	Aluminum cup wheel No. 2, practically a duplicate of cup wheel No. 1, tested in high speed tunnel, with plain bearings.
	9.2	10.4	568	2.66	
	18.9	24.0	638	2.37	
	28.7	37.4	656	2.30	
	38.4	51.0	668	2.26	

[1] The old standard 4-cup wheels were supposed to have arms of the nominal length of 6.72 inches. On the basis of a factor 3.00 such cup wheels would make 500 turns per mile of wind travel. A special gearing was devised for these tests in order that the electrical registrations should show indicated velocities, V, directly in approximate meters per second. This gearing introduced an error of 0.06 per cent. The true value of indicated velocity is, therefore, 0.06 per cent greater than V as tabulated.

TABLE 1.—*Original observations and derived data of anemometer tests in wind tunnel at Bureau of Standards. W=true velocity of wind, V=indicated velocity by the anemometer on the assumption that each cup wheel turn represented a fixed wind travel like 0.50, 0.75, 1.00, 2.00, 2.50 or 3.00 meters, according to an arbitrary factor F and actual length of arm L. Old standard 4-cup wheels.*—Continued

Date and run by serial number	Observed data. Velocities, m/sec.		Derived data		Specifications
	Wind, W	Anemometer indicated, V	Cup turns per mile N, $502.9V \div W$	Factor $W+v$ $F=\frac{10084}{LN}$	
1922 Apr. 21, No. 45.	5.4	5.7	531	2.85	Aluminum cup wheel No. 5, essentially like Nos. 1 and 2, except arms are round, plain bearings, and high-speed tunnel.
	10.0	11.0	553	2.73	
	15.0	18.4	617	2.45	
	20.2	25.5	635	2.38	
	30.2	39.4	656	2.30	
	40.4	53.2	662	2.28	
Apr. 21, No. 46.	6.1	6.1	503	3.01	Round arm, aluminum cup wheel No. 6, practically duplicate of No. 5. Test also in high-speed tunnel; plain bearings.
	10.0	11.7	588	2.57	
	15.0	18.6	624	2.42	
	20.2	25.6	637	2.37	
	30.2	39.6	659	2.29	
	41.0	53.9	661	2.29	
	50.4	67.5	674	2.24	
	60.5	79.6	663	2.28	
Mar. 31, No. 3.	7.3	7.6	524	2.88	Copper cup wheel No. 3 on square arms, otherwise similar to No. 1, except arms have flat metal braces edgewise to wind. Low-speed tunnel; plain bearings. Cup wheel found out of balance.
	10.2	12.1	597	2.53	
	15.4	18.6	607	2.49	
	20.5	25.4	623	2.43	
	25.6	32.1	631	2.40	
	30.7	39.4	645	2.34	
	35.8	46.4	652	2.32	
	38.9	50.6	654	2.31	
Mar. 31, No. 6.	7.3	8.0	551	2.74	Duplicate test of cup wheel No. 3 after wheel was balanced.
	10.2	11.5	567	2.67	
	15.3	18.4	605	2.50	
	20.4	25.2	621	2.43	
	25.5	32.2	636	2.38	
	30.6	39.0	641	2.36	
	35.7	46.0	648	2.33	
	38.8	49.9	647	2.34	
Apr. 8, No. 32.	6.4	6.6	519	2.91	Cup wheel No. 3 as balanced in ball bearings. Tested in high-speed tunnel.
	9.2	9.8	536	2.82	
	18.9	22.6	602	2.51	
	28.8	36.3	634	2.38	
	38.5	49.6	648	2.33	
	50.8	66.0	654	2.31	
	60.9	79.5	656	2.30	
Apr. 8, No. 29.	6.1	6.2	512	2.95	Cup wheel No. 3 as before in plain bearings, high-speed tunnel.
	9.2	9.8	536	2.82	
	18.8	22.6	604	2.50	
	28.7	36.6	640	2.36	
	38.3	49.4	649	2.33	
Apr. 8, No. 30.	6.1	6.2	511	2.96	Copper cup wheel No. 4, similar to No. 3. Tested in high-speed tunnel. Palin bearings.
	9.2	9.9	541	2.79	
	18.9	23.0	612	2.47	
	28.7	36.6	642	2.35	
	38.4	49.8	652	2.32	
Apr. 8, No. 33.	6.2	6.8	552	2.74	Heavy seacoast copper cup wheel No. 7. Cups on heavy square steel arms with flat braces broadside to the wind, large plain bearings. Test in high-speed tunnel. The great difference between this test and those of other like 4-cup wheels is not explainable.
	9.2	10.2	558	2.71	
	18.9	22.0	586	2.58	
	28.8	34.0	594	2.54	
	38.4	45.5	596	2.54	
	50.7	61.2	607	2.49	
	60.8	73.8	611	2.47	

TABLE 2.—*Original observations and derived data of anemometer tests in wind tunnel at Bureau of Standards. W=true velocity of wind, V=indicated velocity by the anemometer on the assumption that each cup wheel turn represented a fixed wind travel, P=0.50, 0.75, 1.00, 2.00, 2.50, or 3.00 meters, according to an arbitrary factor F and actual length of arm L. Miscellaneous 3-cup wheels of various dimensions.*

Date and run by serial number	Observed data Velocities m/sec.		Derived data		Specifications
	Wind, W	Anemometer indicated, V	Cup turns per mile $N=\frac{V}{PW}1609.35$	Factor $W+V$ $F=\frac{10084}{LN}$	
1922					Cup wheel No. 15:
July 21,	7.1	6.3	2856	3.07	d=cup diameter=1.57 inches.
No.56.	10.3	9.4	2937	2.99	L=length of arm=1.15 inches.
	15.4	14.0	2926	3.00	P=assumed travel per turn=
	20.6	19.2	3000	2.92	0.5 meters.
	30.9	29.0	3021	2.90	Ball bearing spindle.
	39.2	36.2	2972	2.95	Low-speed tunnel.
July 21,	7.3	6.8	1999	2.85	Cup wheel No. 16:
No. 57.	10.7	10.2	2045	2.79	d=1.57 inches.
	15.5	15.3	2188	2.69	L=1.77 inches.
	20.7	20.8	2156	2.64	P=0.75 meters.
	31.0	31.5	2180	2.61	Ball bearing spindle.
	38.3	39.4	2207	2.58	Low-speed tunnel.
					Cup wheel No. 17:
July 21,	7.1	6.2	1405	3.04	d=1.57 inches.
No. 56.	10.3	9.5	1484	2.88	L=2.36 inches.
	15.4	14.8	1547	2.76	P=1 meter.
	20.6	20.2	1578	2.71	Ball bearing spindle.
	30.9	31.5	1641	2.60	Low-speed tunnel.
	39.2	39.6	1626	2.63	Cup wheel No. 15 tested simultaneously during this run.
July 21,	7.3	6.4	1411	3.03	Duplicate test cup wheel No. 17.
No. 57.	10.7	6.9	1489	2.87	Cup wheel No. 16 was tested
	15.5	14.9	1547	2.76	simultaneously during this run.
	20.7	20.8	1618	2.64	Cup wheels 15, 16, and 17 are
	31.0	32.2	1672	2.60	small, for use on kites.
	38.3	40.1	1685	2.54	
July 21,	6.7	6.8	1633	2.64	Cup wheel No. 18:
No. 50.	10.2	10.1	1594	2.70	d=4 inches.
	15.3	15.6	1641	2.63	L=2.34 inches.
	20.4	20.6	1625	2.65	P=1 meter.
	30.7	31.3	1641	2.63	Ball bearing spindle.
	37.8	38.6	1643	2.62	Low-speed tunnel.
Apr. 21,	5.6	5.4	776	2.72	Cup wheel No. 19:
No. 47.	10.0	10.2	821	2.57	d=4 inches.
	15.0	15.8	848	2.49	L=4.78 inches.
	20.2	21.5	856	2.46	P=2 meters.
	30.3	33.1	879	2.40	Ball bearing spindle.
	40.4	44.4	884	2.39	High-speed tunnel.
Apr. 21,	6.1	6.0	792	2.66	Cup wheel No. 20:
No. 48.	10.0	10.4	837	2.52	Duplicate of No. 19.
	15.1	16.0	853	2.47	Ball bearing spindle.
	20.2	21.8	868	2.43	High-speed tunnel.
	30.3	33.9	900	2.34	*Cups were deformed at these
	40.4	45.9	914	2.31	velocities, and underregis-
	50.6	57.2	*909	2.32	tered.
	60.7	67.0	*888	2.38	
July 21,	7.1	6.4	726	2.61	Cup wheel No. 21:
No. 51.	10.3	9.4	734	2.58	d=4 inch.
	15.4	14.6	762	2.48	L=5.33 inches.
	20.4	19.5	769	2.46	P=2 meters.
	30.7	30.5	800	2.36	Ball bearing spindle.
	37.8	38.0	809	2.34	Low-speed tunnel.
July 21,	7.2	6.4	715	2.61	Cup wheel No. 25:
No. 53.	10.5	9.7	743	2.51	d=4.5 inches.
	15.4	15.1	789	2.55	L=5.4 inches.
	20.5	20.5	805	2.32	P=2 meters.
	30.8	31.4	820	2.28	Ball-bearing spindle.
	37.9	38.9	826	2.26	Low-speed tunnel.
1923					
July 6,	6.9	6.2	728	2.71	Cup wheel No. 28:
No. 60.	10.1	9.9	789	2.49	d=5 inches.
	15.0	15.1	826	2.38	L=5.14 inches.
	20.0	20.7	833	2.36	P=2 meters.
	30.0	31.8	853	2.30	Ball-bearing spindle.
					Low-speed tunnel.
July 6,	6.7	6.3	757	2.54	Cup wheel No. 31:
No. 61.	10.0	9.4	756	2.54	d=6 inches.
	15.4	14.8	793	2.43	L=5.24 inches.
	20.0	19.7	793	2.43	P=2 meters.
	30.0	30.4	815	2.36	Ball-bearing spindle.
					Low-speed tunnel.
July 6,	6.9	6.4	597	2.58	Cup wheel No. 26:
No. 58.	6.5	5.8	574	2.68	d=4.5 inches.
	9.8	9.4	617	2.50	L=6.55 inches.
	15.0	14.7	631	2.44	P=2.5 meters.
	20.0	20.1	647	2.38	Ball-bearing spindle.
	30.1	31.2	669	2.30	Arms 11 mm in diameter.
	35.0	36.8	677	2.27	Low-speed tunnel.
July 6,	6.8	6.3	596	2.58	Cup wheel No. 26:
No. 59.	10.0	9.6	618	2.49	Arms reduced to 5.6 mm diameter.
	15.0	15.2	652	2.36	Ball-bearing spindle.
	20.0	20.8	670	2.30	Low-speed tunnel.
	30.0	32.0	686	2.24	

TABLE 2.—*Original observations and derived data of anemometer tests in wind tunnel at Bureau of Standards. W=true velocity of wind, V=indicated velocity by the anemometer on the assumption that each cup wheel turn represented a fixed wind travel, P=0.50, 0.75, 1.00, 2.00, 2.50, or 3.00 meters, according to an arbitrary factor F and actual length of arm L. Miscellaneous 3-cup wheels of various dimensions*—Continued.

Date and run by serial number	Observed data Velocities m/sec.		Derived data		Specifications
	Wind, W	Anemometer indicated, V	Cup turns per mile $N=\frac{V}{PW}1609.35$	Factor $W=V$ $F=\frac{10084}{LN}$	
1923					
July 6,	6.7	6.0	577	2.78	Cup wheel No. 30:
No. 63.	10.2	9.8	619	2.59	d=5 inches.
	15.0	15.0	644	2.49	L=6.29 inches.
	20.0	20.6	663	2.42	P=2.5 meters.
	30.0	31.0	665	2.41	Ball-bearing spindle.
	35.0	36.6	674	2.38	Low-speed tunnel.
July 6,	6.8	6.3	596	2.58	Cup wheel No. 32:
No. 62.	10.1	10.2	650	2.36	d=6 inches.
	15.0	15.2	652	2.36	L=6.56 inches.
	20.0	21.0	676	2.27	P=2.5 meters.
	30.0	31.9	685	2.24	Ball-bearing spindle.
					Low-speed tunnel.
1922					
July 21,	6.9	5.7	443	2.65	Cup wheel No. 22:
No. 52.	10.3	8.7	453	2.59	d=4 inches.
	15.3	14.0	491	2.39	L=8.59 inches.
	20.4	19.2	505	2.32	P=3 meters.
	30.6	29.7	521	2.25	Ball-bearing spindle.
July 21,	37.3	36.9	531	2.21	Low-speed tunnel.
No. 54.	7.3	6.0	441	2.66	Cup wheel No. 27:
	10.5	9.0	465	2.51	d=4.5 inches.
	15.4	14.2	495	2.38	L=8.59 inches.
	20.5	19.4	508	2.31	P=3 meters.
	30.8	29.8	519	2.27	Ball-bearing spindle.
	38.0	37.4	528	2.22	Low-speed tunnel.
July 21,	6.9	6.2	482	2.44	Heavy brass cup wheel No. 33:
No. 55.	10.3	9.5	495	2.38	d=6.11 inches.
	15.4	14.8	516	2.28	L=8.56 inches.
	20.6	19.8	516	2.28	P=3 meters.
	25.7	24.7	516	2.28	Ball-bearing spindle.
					Low-speed tunnel.

TABLE 3.—*Tests of 2 Friez magneto anemometers equipped with standard 3-cup wheels. Run 64, magneto built without wind vane; run 65, another magneto with wind vane; run 66, same magneto with vane removed. Indicated velocities read from voltmeter scale graduated directly in miles per hour.*

Date and run	Observed data. Velocity m/hr.		Derived data		Specifications
	Wind, W'	Voltmeter velocity V	Cup turns per mile, $N=\frac{640V}{W'}$ approximate [1]	Factor $W+v$ $F=\frac{10084}{LN}$	
1929					
June 7,	12.6	12.6	640	2.52	Standard 3-cup wheel:
No. 64.	13.6	13.3	626	2.58	d=5.02 inches.
	23.6	23.7	643	2.51	L=6.254 inches.
	28.9	29.6	656	2.46	P=2.5 meters.
	33.6	34.8	663	2.43	This magneto built without wind vane.
	41.0	43.3	676	2.39	Large tunnel, open air; diameter, 10 feet.
	45.6	49.2	691	2.33	
	45.8	48.2	673	2.40	
	51.9	56.0	690	2.34	
	57.4	62.3	695	2.32	
	62.6	70.3	716	2.25	
	69.2	75.7	698	2.31	
	61.0	66.8	701	2.30	
	50.2	54.0	688	2.34	
	44.9	48.5	691	2.33	
	40.7	42.6	670	2.40	
	27.5	27.7	645	2.50	
	12.6	12.5	635	2.54	

[1] To secure N accurately in any test requires that the instruments be provided with some form of worm wheel counting and registration gear. Without this integrating mechanism in the present case, N could be computed only approximately from eye readings of the slightly oscillating needle of the voltmeter, which indicated only the momentary angular cup velocities converted into miles per hour, upon the inexact assumption that the cup wheels made 640 turns per mile of wind travel, that the magneto generates 6 volts per 1,000 revolutions per minute, and that the voltmeter is correctly scaled to miles per hour on this basis. The scattered distribution of these observations, as plotted in figure, indicates the inexactitude of the results as a whole. Certain corrections are recognized as being required, but these are not sufficiently known to justify application.

TABLE 3.—*Tests of 2 Friez magneto anemometers equipped with standard 3-cup wheels. Run 64, magneto built without wind vane; run 65, another magneto with wind vane; run 66, same magneto with vane removed. Indicated velocities read from voltmeter scale graduated directly in miles per hour*—Continued

Date and run	Observed data. Velocity m/hr.		Derived data		Specifications
	Wind, W''	Voltmeter velocity V	Cup turns per mile, $N=\frac{640V}{W_{\prime}}$ approximate	Factor $W+v$ $F=\frac{10084}{LN}$	
1929					
June 7, No. 65.	12.6	12.7	646	2.50	Standard 3-cup wheel:
	19.2	20.0	667	2.42	Similar magneto, but equipped
	24.9	25.0	643	2.51	with wind vane.
	31.1	32.3	665	2.43	d=5.03 inches.
	35.5	38.3	690	2.34	L=6.244 inches.
	42.8	45.4	679	2.38	P=2.5 meters.
	45.7	50.0	700	2.31	Large tunnel, open air.
	52.4	56.8	694	2.31	
	56.8	63.5	715	2.26	
	57.8	64.0	720	2.24	
	64.6	71.5	708	2.28	
	69.6	77.0	708	2.28	
	59.0	65.3	708	2.28	
	46.5	50.7	698	2.31	
	31.9	33.4	670	2.41	
	20.3	20.3	631	2.56	
June 7, No. 66.	14.1	13.0	590	2.74	Same cup wheel and magneto, with
	21.8	21.4	628	2.57	vane removed, necessitating an im-
	26.0	26.7	657	2.49	provised substitute for ball bearing.
	31.7	33.2	670	2.41	Large tunnel, open air.
	39.2	41.5	678	2.38	
	46.3	50.4	697	2.32	
	49.2	54.3	706	2.29	
	55.9	61.5	704	2.29	
	60.5	66.5	703	2.30	
	65.4	72.2	707	2.28	
	70.6	78.3	710	2.27	

TABLE 4.—*Data and constants for hyperbolic equations, asymptotes parallel to coordinate axes, giving the relations between N, number of turns per mile of wind velocity, and W, the wind velocity in meters per second*

EQUATION, $N=\frac{b(W-W_o)}{W+a}$

Case	Cup wheel			Max. $N\,b$	Curvature a	Friction W_o	Remarks
	No.	Arms L	Cups diameter, d				
		Inches	*Inches*				
1	18	2.34	4.0	1,650.0	−0.113	0.30	Shortest arms for 4-inch cups.
2	34 35	3.81 3.92	4.5 5.0	1,100.0	.002	.67	Two 1/1000-mile wheels tested on Friez no vane magneto.
3	19 20	4.78 4.78	4.0 4.0	922.5	.847	.30	Duplicate wheels; 2 runs.
4	28	5.14	5.0	893.1	1.064	.30	Single run on 1 wheel.
5	31	5.24	6.0	835.2	.548	.30	Do.
6	21	5.33	4.0	834.5	1.040	.30	Do.
7	25	5.40	4.5	857.7	1.013	.30	Do.
8	--- ---	6.25 6.24	5.02 5.03	745.4	.909	.67	2 standard 3-cup wheels tested on 2 Friez magnetos.
9	30	6.29	5.0	696.6	.919	.30	Only 3-cup wheel close to standard tested in tunnel, velocity range 7 to 35 m/sec.
10	26 26	6.55 6.55	4.5 4.5	704.8	1.030	.30	3-cup wheel, thick arms; 3-cup wheel arms thinner.
11	32	6.56	6.0	711.6	.841	.30	Nos. 8, 9, 10, 11 nearly like 3-cup standard.
12	----	6.677	4.0	686.4	1.313	.30	Mean of 68 tests on aluminum 4-cup wheels over maximum range of velocity 4–61, m/sec.
13	----	6.677	4.0	678.2	1.582	.30	Mean of 33 tests to highest velocity of copper 4-cup wheels.
14	33	8.56	6.11	530.1	.093	.50	Heavy brass cup, long arms.
15	22 27	8.59 8.59	4.0 4.5	551.0	1.527	.30	2 long arm cup wheels.

NOTE.—Nos. 12 and 13 in this table relate to the large number of tests on the 4-cup anemometers. A few of these tests were carried to the extreme velocity of 60 meters per second. All the remaining cases represent often only a single run on 3-cup wheels, and of these only 8, 9, 10, and 11 represent anemometers which are fairly comparable, not identical, with the present 3-cup standard. Only in case 3, duplicate cup wheels 19 and 20, did the velocity exceed 35 meters per second, and in this case the cups were deformed above 40 meters per second, leaving the performance of the 3-cup wheels at high velocities in doubt.

WET-BULB DEPRESSION AS A CRITERION OF FOREST-FIRE HAZARD

By J. R. LLOYD

[Weather Bureau, Chicago, Ill., March 10, 1932]

Ever since the inauguration of the fire-weather work by the Weather Bureau in the forested areas of this country there has been a need for a convenient scale or formula for use in estimating the combined effects of temperature and relative humidity on forest-fire hazard. It has been known for a long time that both temperature and relative humidity exert an influence on fire hazard. However, these two elements are so associated that it is very difficult to assign proper values to each. The writer has for several years been engaged on fire-weather work in the upper Great Lakes region, and therefore has more than an ordinary interest in this problem. If a single scale or formula could be found that would measure the combined effects of temperature and relative humidity on forest-fire hazard to a reasonable degree of accuracy it would go a long way in solving one of the most difficult problems in fire-weather work.

In order to start on this problem it was necessary to gather a lot of data on forest fires. The writer chose the season of 1930 for fire data because of the fact that most of the season was bad from a hazard standpoint. Fire report cards were sent to the district forest rangers, who reported on about 5,000 separate fires that occurred in Wisconsin and Michigan during 1930. One report card was used for each fire, on which was shown the time of beginning and of ending of the fire, the area burned, the type of forest cover burned, and the kind of soil, in general, that was burned over. With this information at hand and with the weather data that had been collected from several fire-weather stations in the forested area, it was possible to attack the problem from several angles, if necessary.

It was decided to chart each fire against the temperature and relative humidity that prevailed at the time the fire broke out. The accompanying chart, Figure 1, shows the manner in which this was done, except the chart as originally prepared showed in colors the sizes of the fires according to several different size classifications, which can not be shown on the chart herewith. Only the fire reports from the districts that had weather observing stations and reliable records were used. By way of explanation of the chart, it should be said that each dot represents a fire, and that the position of each dot on the chart indicates the temperature and the relative humidity that prevailed shortly before the fire was first noticed by the forest guard. It should be noted that each degree of temperature is represented by a band 5 millimeters wide running vertically on the chart, and each 1 per cent of relative humidity by a 5 millimeter band running horizontally across the chart. The fires are charted in the 5-millimeter squares at the intersections of these bands that represent temperature and relative humidity. It may be seen that in some of the 5-millimeter squares as many as eight fires have been charted. A total of 3,002 fires were charted.

When the chart is examined carefully it will be found that it presents some very interesting features. Probably the most outstanding feature is the heavy preponderance